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Invited Paper

A linearly chirped seed suppresses SBS in high-power fiber amplifiers, allows coherent combination, and enables long delivery fibers

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ABSTRACT

When seeding a high power fiber amplifier with a frequency-chirped seed, the backward Brillouin scattering can be kept at the spontaneous level because the coherent laser/Stokes interaction is interrupted. Operating a conventional vertical cavity surface-emitting diode laser in an optoelectronic feedback loop can yield a linear frequency chirp of $\sim 10^{16}$ Hz/s at a constant output power. The simple and deterministic variation of phase with time preserves temporal coherence, in the sense that it is straightforward to coherently combine multiple amplifiers despite a large length mismatch. The seed bandwidth as seen by the counter-propagating SBS is large, and also increases linearly with fiber length, resulting in a nearly-length-independent SBS threshold. Experimental results at the 600W level will be presented. The impact of a chirped seed on multimode instability is also addressed theoretically.

Keywords: fiber amplifiers, chirped lasers, stimulated Brillouin scattering, multi-mode instability, coherent combining

1. INTRODUCTION

Bottlenecks in the scaling of high power fiber lasers arise because of heating due to the finite quantum defect and nonlinear effects, e.g. stimulated Brillouin scattering, due to the large intensity×length product. Efforts to raise the power threshold include (a) reducing the line-center Brillouin gain by combining materials with positive and negative elasto-optic coefficients,[1] or tailoring the acoustic index to avoid guiding the acoustic wave,[2,3] (b) reducing the effective Brillouin gain by using a seed linewidth much wider than the Brillouin bandwidth,[4,5,6] or a Brillouin bandwidth larger than the seed linewidth,[7,8,9] (c) lowering the laser intensity by enlarging the fiber core, (d) minimizing the required active fiber length by pumping at a wavelength where the absorption cross section is maximum, and doping as heavily as possible. Conventional approaches to broadening the seed linewidth reduce the coherence length making it difficult to coherently combine multiple fiber amplifiers. For example, a seed bandwidth of 20 GHz (coherence length in fiber = 10 mm) will require path length matching of less than 1 mm to maintain high coherence. The present work describes the use of a linearly frequency-chirped laser to seed multiple Yb fiber amplifiers while suppressing SBS. This approach is compatible with the other techniques for suppressing SBS, except those that increase the Brillouin linewidth. We also describe the use of acousto-optic frequency shifters and feedback circuitry to maintain coherence between two 20 W fiber amplifiers despite path length differences on the order of 10 cm.

2. CHIRPED DIODE LASER TECHNOLOGY

The frequency chirping associated with modulation of laser diode current at sub-MHz frequencies results from the ohmic heating of the active region and the associated shrinking of the bandgap and red-shift of the emission. It is onerous in telecommunications but can be exploited in other applications, e.g. chirped laser radar, and, as recently shown, in

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seeding high power fiber lasers. A highly linear chirp can be obtained through the use of a phase-locked loop. The first report of this technique achieved a 100 GHz sweep in 10 ms, or 10^{13} Hz/s, at a wavelength of 0.83μ. More recent development at 1.5μ increased the chirp to 100 GHz in 1 ms, or 10^{14} Hz/s by a combination of two techniques: (i) an open-loop pre-distortion of the input current into the laser, and (ii) phase-locking the chirp to a reference electronic signal. When the system is in lock, the chirp is determined by the frequency of the reference signal. The latest generation of phase-locked current-modulated chirped diode lasers at 1.06μ and 1.5μ have achieved 500 GHz in 0.1 ms, or $5 \cdot 10^{15}$ Hz/s. To maintain a constant output power, a second feedback loop is used to control the semiconductor optical amplifier.

The frequency of the seed can be made to follow a sawtooth or a triangular waveform in time. To avoid SBS occurring at the turning points in the waveform, where the chirp passes through zero, a dual-source has been implemented. A controller synchronizes the two lasers and provides a trigger to the electro-optic 2×1 switch (Fig. 1a). By adjusting the relative phases of the two frequency sweeps, a triangle wave or sawtooth can be generated (Fig. 1b).

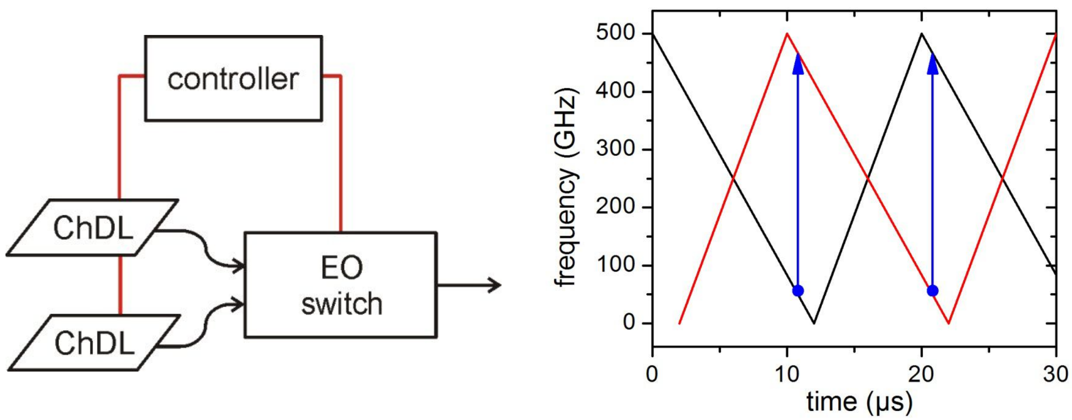


Fig. 1 (a) Dual source, consisting of two synchronized, out of phase chirped diode lasers with a 2x1 electro-optic switch. (b) Frequency vs time waveform, showing the transitions (blue line) between source one (black line) to source two (red line), in the case of a negative sawtooth.

3. SBS SUPPRESSION

The SBS originates from spontaneous Brillouin scattering *throughout* a fiber, but the suppression mechanism can be intuitively understood by considering the gain experienced by light originating at $z = L$. The backward-propagating wave is a superposition of a range of frequencies around the Stokes frequency given by $\nu_S = \nu_L - \Omega$. For an unchirped laser, a Stokes frequency component that is on resonance at $z = L$ will remain on resonance as it propagates backwards. For a chirped laser, the gain for the Stokes wave that begins on resonance will decrease as it propagates backwards (Fig. 2). If the Brillouin gain is Lorentzian, the gain for that component will follow a Lorentzian in space, decreasing to half its original value within a distance $c\Delta\nu_B/(4\beta \mathrm{n})$, where β is the chirp.

For a laser with positive chirp, a spectrum of blue-shifted Stokes frequencies will come into resonance within the length of the fiber. The Stokes frequency that comes into resonance in the middle of the fiber will have the largest gain when integrated over z. The full width at half maximum gain for this component will be $c\Delta\nu_B/(2\beta \mathrm{n})$. For a Brillouin linewidth of 100 MHz (FWHM) and a chirp of 10^{16} Hz/s, a Stokes frequency component that comes into resonance in the middle of the fiber will experience Brillouin gain over a distance of ~1m.

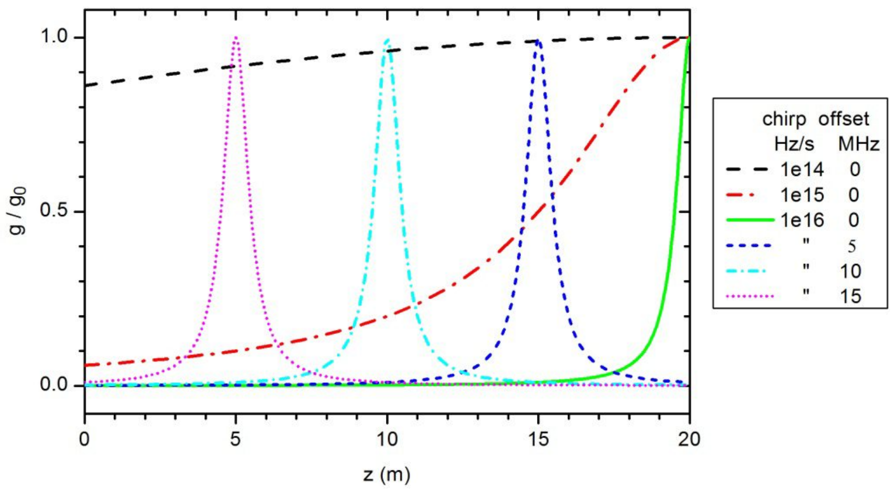


Fig. 2 Normalized Brillouin gain as a function of position in the fiber, for various laser chirps and Stokes frequency components at different offsets from resonance, from an adiabatic model.[10] Brillouin linewidth 100 MHz.

4. TESTING SBS SUPPRESSION AT 600W

The seed laser described in Section 2 has been tested with a Yb fiber amplifier pumped by 976-nm diodes. The output power is limited by SBS in the final stage. The final stage fiber is double clad, with a core diameter of 20μ and an inner cladding diameter of 400μ. Three photodiodes monitor the power entering the final stage, the output power, and the backward power leaving the final stage (Fig. 3a). For a negative-chirp sawtooth, the power entering the final stage has unintentional modulation (Fig. 3b, red trace) due to wavelength- and polarization-dependent loss/gain and dispersion in the components between the seed lasers and the the pre-amplifier, including the electro-optic switch and the taps. The output power (top black trace) has about the same amount of modulation. The backward SBS measured with a fast photodiode shows the pulses characteristic of the initiation from spontaneous scattering (bottom black trace).

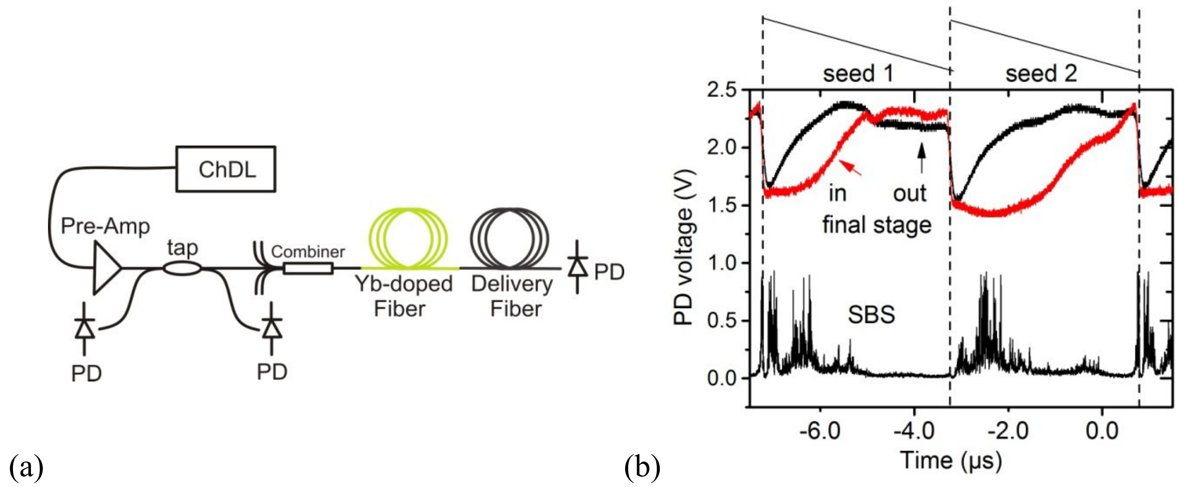
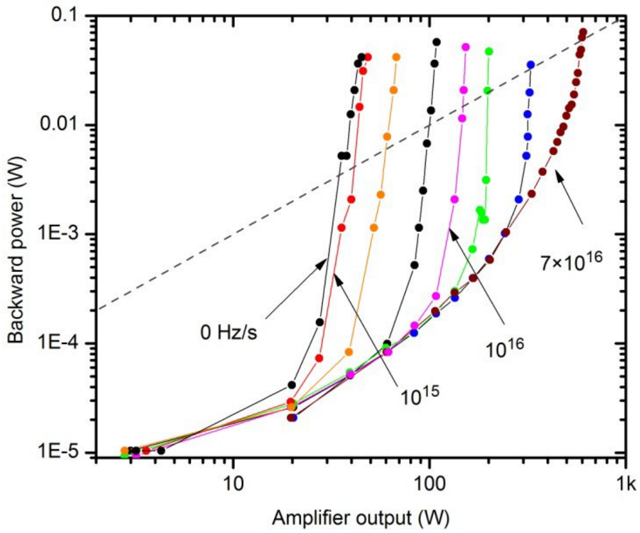


Fig. 3 (a) Experimental apparatus for measuring input power to the final stage, backwards SBS power, and output power. (b) Oscilloscope traces from the three photodiodes, taken at an output power of 600 W. The modulation on the input to the final stage is due to phase and amplitude dispersion in the pre-amplifier. The frequency waveform is a negative sawtooth.

The backward SBS power was also measured with an averaging detector, and then plotted vs the output power (Fig. 4a). The output power was varied by changing the current to the diodes pumping the final stage. The backward power clearly shows a threshold behavior. We define threshold as the point where the backward power equals 10^{-4} times the output power, and can then plot the threshold output power vs chirp (Fig. 4b). The threshold output power (black squares) is clearly increasing linearly with chirp, as shown by the dashed red line. Based on this, we expect the next generation of chirped diode lasers with a factor of ten higher chirp to enable ~6 kW output powers. As shown in the next section, chirped seed amplifiers will also be coherently combinable.



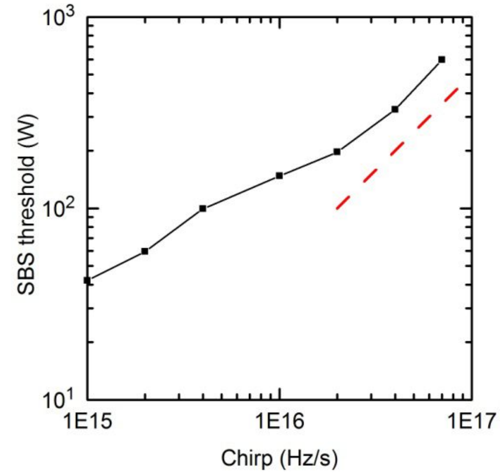


Fig. 4 (a) Backward power from the final stage vs amplifier output power, for various chirps. The dashed line represents a backward power equal to 10^{-4} times the output power, used here to define SBS threshold. (b) SBS threshold vs chirp. The dashed line represents a linear scaling of threshold with chirp.

5. COHERENT COMBINING AT 40W

Recent work on coherent combining of fiber amplifiers, path length matching has been achieved by using a variable delay line and an electro-optic phase shifter.[11] A fiber stretcher can also compensate for ~3 mm of path length difference with a frequency response of ~1 kHz. Our approach relies on an acousto-optic variable-frequency shifter with a nominal shift in the range 100-400 MHz. The configuration for coherent combining has the seed divided into a reference and a channel for each amplifier. Each phase-locked loop has a digitally synthesized local oscillator; all are synchronized by a master clock. The relative phase of each output beam can be adjusted at the start of each scan.[12] Scan periods range from 10 μs – 1 ms.

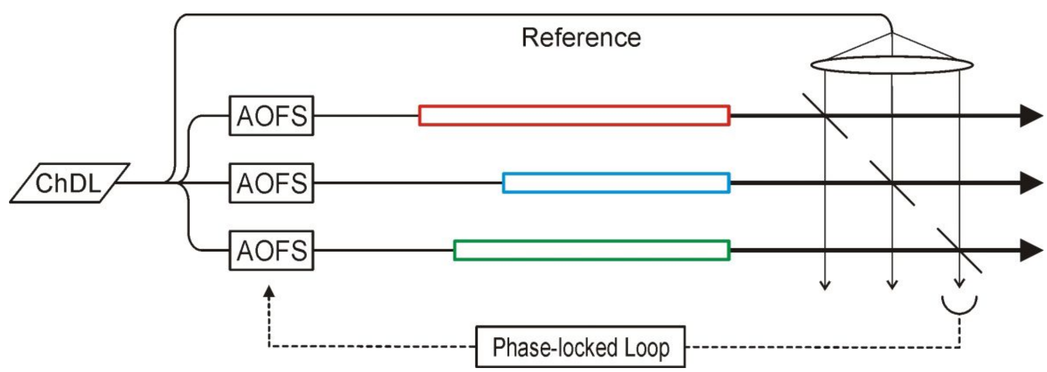


Fig. 5 Configuration for coherently combining three fiber amplifiers. A small fraction of the output of each amplifier is interfered with the reference; the signal from the photodiode is sent to the phase-locked loop. The feedback ensures that the exit beams are all at the same frequency and have a fixed, user-selectable relative phase.

Interference fringes were observed by overlapping the outputs of two 20-W Yb fiber amplifiers (Fig. 6a-d). The fringe visibility depends on many factors in addition to the residual phase error of the feedback loop: the quality of the two wavefronts, how well the intensity profiles match, and whether the polarizations are parallel. The residual phase error can be estimated via an I/Q demodulation of the signal coming from the photodiode in the feedback loop (Fig. 6e). For the case of a chirp equal to $2.4 \cdot 10^{14}$ Hz/s and a path length mismatch of 1.7 cm, the residual phase error is 0.15 rad, ignoring the transient at $t = 2$s between sweeps. This leads to a theoretical coherent combining efficiency of $\eta = 98.9\%$. For a mismatch of 39 cm, the residual phase error was 0.42 rad, i.e. $\eta = 91.2\%$.

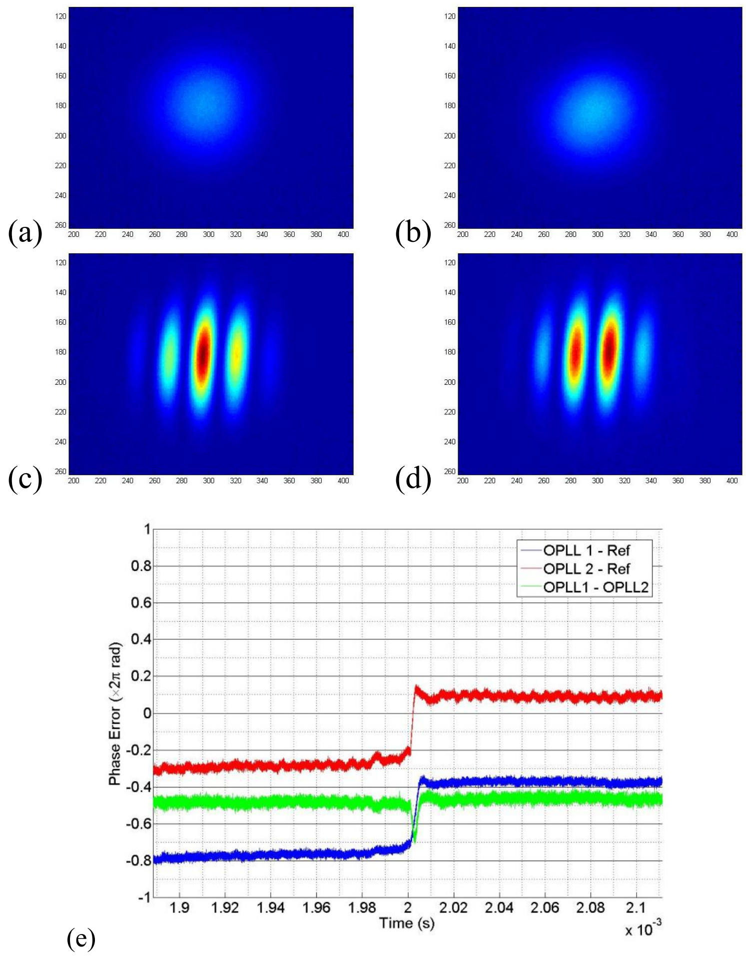


Fig. 6 Intensity profiles of the beams exiting a two-channel Yb fiber amplifier; each channel emitting 20 W. (a) Channel A alone, (b) channel B, (c) both channels present and in phase, (d) out of phase. (e) The top (red) trace is the phase of channel A relative to the reference, as obtained by I/Q demodulation. The bottom (blue) trace is the phase of channel B relative to the reference. The middle (green) curve is the relative phase of channels A and B.

6. MULTIMODE INSTABILITY SUPPRESSION

For applications which require high spatial brightness, another bottleneck in the scaling of large mode area fiber lasers is the multimode instability that occurs at high-average-power. It is generally attributed to either (a) transverse spatial hole burning, or (b) a coupling between modes created when their interference gives rise to a spatially periodic variation of the gain or index in the core along the longitudinal direction. The analysis in this section shows that the problem of a coupling between the LP_{01} and LP_{11} modes can be avoided with a chirped seed.

The effective index as a function of $V = k\, a\, NA$ is shown in Fig. 7a for the LP_{01} and LP_{11} modes in a typical LMA fiber. V is varied by changing the optical frequency; the fiber parameters ($NA = 0.06$ and core diameter $2a = 20$μ) are fixed. The vertical dashed line indicates $V = 3.56$ associated with a wavelength of 1.06μ. The wavevector of the grating formed between the two modes is shown in Fig. 7b. At 1.06μ, $g \cong 2.87 \cdot 10^3\ \mathrm{m}^{-1}$, i.e. the grating period $\Lambda \cong 0.35$ mm. Because the slope of $g(V)$ is non-zero, the grating vector will change as the seed sweeps in frequency. For frequency sweeps of a few percent, the change Δg that occurs during a sweep $\Delta\nu = \nu_1 - \nu_2$ can be approximated by $\Delta g = (dg/d\nu)\Delta\nu$ (Fig. 7c).

Higher order modes in the final stage amplifier, e.g. the LP_{11} mode, are typically excited at the splice between a single-mode fiber and the LMA fiber. If the relative phase between the two modes is fixed at the splice, the grating will expand or contract from that point. At a distance $L_\pi = \pi/\Delta g$ from the splice, the spatial interference when the seed is at ν_1 and at ν_2 will be π out of phase. L_π is shown in Fig. 7d as a function of wavelength, for frequency sweeps of 0.5, 1.0, and 2.0 THz.

If the seed sweep time is short compared to the thermal diffusion time, any thermally-induced change in gain or index will be washed out after a distance L_π. Because the grating period is an order of magnitude larger than the core diameter, the relevant diffusion time is $\tau = a^2\rho C/\kappa$, where ρ is the density, C is the specific heat, and κ is the thermal conductivity. For a 20μ fused silica core, $\tau = 0.11$ ms. For a 30μ core diameter, $\tau = 0.25$ ms. In our system, the high chirps are obtained at sweep time of less than 0.1 ms, so the thermally induced grating should be negligible after a distance L_π from the splice.

If the seed tunes over a range of 2 THz (8 nm at 1.06μ), $L_\pi \cong 0.5$ m (Fig. 7d). For a 10m active fiber, this could represent an order of magnitude increase in the threshold for multimode instability.

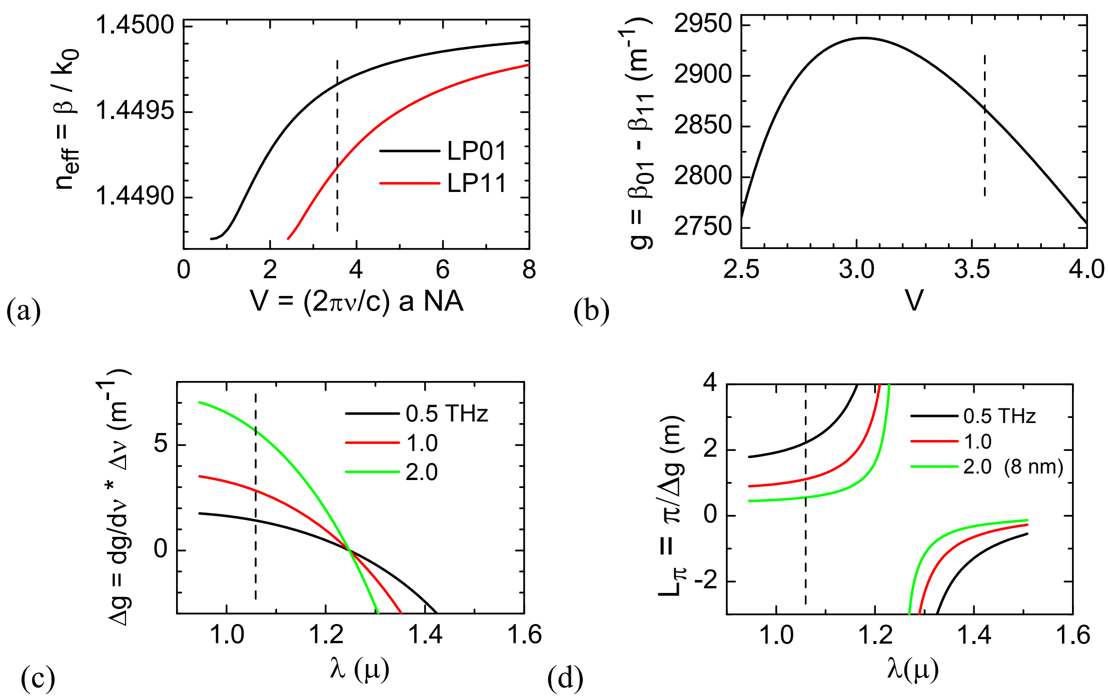


Fig. 7 (a) Effective index as a function of the V number (normalized frequency) for the two lowest order modes of a step index fiber. fiber frequency for the two lowest order modes in a step index LMA fiber (NA=0.06 and core diameter $2a = 20$μ). (b) The wavevector of the grating formed by the interference of the two modes. (c) The change in grating vector for sweeps of 0.5-2.0 THz. (d) L_π as a function of wavelength, for sweeps of 0.5-2.0 THz.

7. CONCLUSION

Chirped seed amplification has been shown experimentally to raise the threshold for stimulated Brillouin scattering in a Yb fiber amplifier. For a chirp of $7{\cdot}10^{16}$ Hz/s, the SBS threshold was raised to 600 W, compared to a threshold of 40 W at zero chirp. Furthermore, we demonstrated that the threshold scales linearly with chirp, so that the next generation of chirped seed lasers will enable multi-kW coherently-combinable fiber amplifiers. The seed bandwidth, as seen by the counter-propagating SBS, increases linearly with delivery fiber length, enabling SBS suppression in long delivery fibers. Lastly, the large mode-hop-free tuning range available from vertical cavity surface emitting lasers also provides a path to suppressing multimode instability, another bottleneck in the scaling of high power fiber lasers.

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